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The impact of hearing aids and age-related hearing loss on auditory plasticity across three months – An electrical neuroimaging study

Giroud, Nathalie ; Lemke, Ulrike ; Reich, Philip ; Matthes, Katarina L ; Meyer, Martin

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The impact of hearing aids and age-related hearing loss on auditory plasticity across three months – an electrical neuroimaging study

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Abstract

The present study investigates behavioral and electrophysiological auditory and cognitive-related plasticity in three groups of healthy older adults (60-77 years). Group 1 was moderately hearing-impaired, experienced hearing aid users, and fitted with new hearing aids using non-linear frequency compression (NLFC on); Group 2, also moderately hearing-impaired, used the same type of hearing aids but NLFC was switched off during the entire period of study duration (NLFC off); Group 3 represented individuals with age-appropriate hearing (NHO) as controls, who were not different in IQ, gender, or age from Group 1 and 2. At five measurement time points (M1-M5) across three months, a series of active oddball tasks were administered while EEG was recorded. The stimuli comprised syllables consisting of naturally high-pitched fricatives (/sh/, /s/, and /f/), which are hard to distinguish for individuals with presbycusis. By applying a data-driven microstate approach to obtain global field power (GFP) as a measure of processing effort, the modulations of perceptual (P50, N1, P2) and cognitive-related (N2b, P3b) auditory evoked potentials were calculated and subsequently related to behavioral changes (accuracy and reaction time) across time.

All groups improved their performance across time, but NHO showed consistently higher accuracy and faster reaction times than the hearing-impaired groups, especially under difficult conditions. Electrophysiological results complemented this finding by demonstrating longer latencies in the P50 and the N1 peak in hearing aid users. Furthermore, the GFP of cognitive-related evoked potentials decreased from M1 to M2 in the NHO group, while a comparable decrease in the hearing-impaired group was only evident at M5. After only twelve weeks of hearing aid use of eight hours each day, we found a significantly lower GFP in the P3b of the group with NLFC on as compared to the group with NLFC off.

These findings suggest higher processing effort, as evidenced by higher GFP, in hearing-impaired individuals when compared to those with normal hearing, although the hearing-impaired show a decrease of processing effort after repeated stimulus exposure. In addition, our findings indicate that the acclimatization to a new hearing aid algorithm may take several weeks.

Words: 342

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Key Words: cognitive hearing, hearing impairment, longitudinal plasticity, auditory learning, non-linear frequency compression, hearing aids, older adults, speech processing, processing effort

Highlights

- Presbycusis leads to higher processing effort as evidenced by higher global-field power (GFP) in auditory evoked potentials (N2b, P3b).
- Hearing-impaired older adults have delayed longitudinal auditory plasticity as compared to normal-hearing older adults.
- It takes several weeks to acclimatize to a new hearing aid algorithm.

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1. Introduction

Peripheral age-related hearing loss (presbycusis) caused by damage to the cochlea or the auditory nerve (Chertoff and Jacobsen, 2012) challenges the central auditory system by delivering a disrupted acoustic signal to the cortex. Hearing aids (HA), the most common treatment for presbycusis, have been developed to restore the signal by amplifying sounds in order to improve audibility. Furthermore, intelligibility of spoken utterances can be supported by applying noise reduction algorithms in HA. Although improvement in speech intelligibility has been shown in aided compared to unaided listening conditions (Coez et al., 2010), it remains unclear if and how central auditory processing changes as a function of HAs.

To date, only a handful of studies have examined early auditory evoked potentials (AEP) such as the P50, the N1, and the P2, and this while young, normal-hearing listeners were fitted with hearing aids for the first time. Comparing aided with unaided listening conditions, some studies reported increases in the peak amplitude of AEPs (Miller and Zhang, 2014; Tremblay et al., 2006a) while others reported a decrease of amplitudes (Billings et al., 2011), delayed latencies (Marynewich et al., 2012; Miller and Zhang, 2014), or no significant differences (Billings et al., 2007; Marynewich et al., 2012). Thus, these results remain difficult to interpret for two reasons. First, these studies applied passive paradigms that do not allow for the direct relation of neurophysiological data to behavior, which would have made less ambiguous interpretations of the decreases and increases in amplitudes and latencies possible. Second, it remains unclear to what extent these results apply to older adults, the group which typically suffers from presbycusis. Nevertheless, two feasibility studies showed that the acoustic change complex (ACC) (Tremblay et al., 2006b) and the speech-evoked envelope following response (EFR)

(Easwar et al., 2015) can be reliably recorded in older hearing aid users. The ACC is a cortical auditory evoked potential elicited in response to an acoustic change (Kim, 2015) and the EFR is a phase locked response to the stimulus envelope frequency (Picton et al., 2003), both of which are measurable with scalp EEG. Furthermore, one other study reported an increase of the P2 amplitude in response to passively presented lower tones and a P2 amplitude decrease in response to passively presented higher tones for aided compared to unaided listening in older adults with age-related hearing loss (Bertoli et al., 2011).

In this paper we systematically addressed the shortcomings of the previous research outlined above by using an active oddball paradigm to assess accuracy and reaction time of oddball detection and by comparing the latencies and global field power (GFP), used here as a correlate for processing effort (Lemke and Besser, 2016), of early perceptual AEPs (P50, N1, P2) and also later cognitive-related AEPs (N2b, P3b) in older adults with moderate presbycusis who were experienced hearing aid users and an age matched control group without hearing loss. Here we define processing effort as the additional resources allocated to a listening task in order to meet the task goal under adverse listening conditions (Lemke and Besser, 2016) and we consider the GFP[1] of the AEPs to be its neurophysiological marker (Pichora-Fuller et al., 2016). The use of GFP as obtained by a topographical microstate approach has several advantages when compared to classic one-electrode or one-electrode-pool analyses: First, single electrodes do not have to be chosen manually. Second, topographical measures are reference independent (Koenig et al., 2014; Lehmann and Skrandies, 1980, 1984). Third, topographical dissimilarities between conditions or groups can be interpreted directly,

[1] We compare the mean GFP and the latency of the peak GFP of the AEPs from the current study with the peak amplitude and peak latency respectively from previous studies.

as they reflect differences in the configuration of the underlying neural networks (Murray et al., 2008; Vaughan, 1982). Fourth, the use of a temporal filter when applying the microstate approach (Koenig et al., 2014; Murray et al., 2008) allows for the identification of temporally stable topographical configurations, which can then be analyzed in a data-driven manner, and thus forgoing the need to define arbitrary time windows of interest in an ERP time course a priori (Giroud et al., 2017; Kühnis et al., 2013; Michel et al., 2009; Murray et al., 2008; Pascual-Marqui et al., 1995). Also, GFP of the N2b and the P3b has previously been shown to reflect longitudinal auditory plasticity in younger adults (Giroud et al., 2017).

Investigating the longitudinal modulations of cognitive-related AEPs is crucial, as several behavioral studies have found facilitating effects of hearing aids on cognitive-related auditory processes (Doherty and Desjardins, 2015; Lavie et al., 2015). In addition, we followed the two groups for three months (measurement time points M1-M5) in order to study central auditory plasticity as a function of the HA time of usage. Longitudinal research to investigate within-group changes across time is much needed in this field, but still rare. Previous longitudinal research on older hearing aid users mainly focused on the predictive value of individual working memory capacity on behavioral speech understanding in different aided conditions (Cox and Xu, 2010; Ng et al., 2014; Rudner et al., 2011). Moreover, in our study, the hearing-impaired group was further divided into two subgroups, one of which was provided with traditional amplification hearing aids, while the other was equipped with a specific hearing aid feature, namely nonlinear frequency compression (NLFC).

NLFC is a common hearing aid feature in which the high-frequency signal, typically no longer accessible to the older hearing-impaired, is compressed into a lower frequency range. It only compresses the signal above a certain threshold which is determined

individually (McDermott and Henshall, 2010). NLFC does not compress lower frequencies in order to avoid artifacts in vowels and it has been reported to improve the recognition of high-frequency consonants, such as fricatives and monosyllabic words (Alexander, 2016; McCreery et al., 2014; Wolfe et al., 2010, 2011, 2015), although not all study participants benefit from NLFC to the same extent (Bohnert et al., 2010; Ching et al., 2013; Hillock-Dunn et al., 2014; Simpson et al., 2005, 2006).

At M1, we predicted longer latencies in P50, N1, and P2 in hearing aid users compared to those with age-appropriate hearing as has been shown in within-subject designs in younger adults (Korczak et al., 2005; Marynewich et al., 2012; Miller and Zhang, 2014) and in studies comparing CI users to those with normal hearing (Finke et al., 2016). Further, for all groups, we expected to find increases of oddball detection accuracy, decreases of reaction time and decreases in AEP latencies across the measurement time points as was shown in a similar experiment with younger adults (Giroud et al., 2017). Importantly, we also expected to find group * M interactions from M2 to M3 revealing stronger increases of accuracy and stronger decreases of reaction time and AEP latencies for normal-hearing participants as compared to the hearing impaired. This is because the central auditory system of hearing aid users is presumed to adapt to hearing aid use for several weeks. This adaption is necessary to appropriately process the auditory stimulus material altered by the hearing aid (Wolfe et al., 2011, 2015). We further predicted that the group with NLFC on would show stronger increases in detection accuracy and decreases in reaction time and AEP latencies compared to the group with pure amplification (Alexander, 2016; Wolfe et al., 2011, 2015). Moreover, we expected that usage of NLFC would lead to stronger decreases in processing effort, measured by the GFP of the N2b and P3b, when compared to the group without NLFC (Hällgren et al., 2005; Hornsby, 2013; Rudner, 2016; Tremblay and Backer, 2016).

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2. Materials and Methods

2.1. Participants

Thirty older adults with moderate age-related hearing loss were recruited through local audiologists. They were all experienced hearing aid users for at least one year, but had no experience with NLFC as used in SoundRecover. At the start of the study each participant received two new binaural hearing aids, model Phonak Ambra M H2O, which were fitted to their individual audiograms by a licensed audiologist during three sessions, each separated by an interval of one week. Twenty-four participants used custom-made SlimTips due to small hearing canals or non-acceptation, and six used standard domes. The vent was determined using Phonak designed technology AOV (acoustically optimized vent) to ensure the correctly-sized vent for each custom-made SlimTip. The hearing-impaired participants were divided randomly into two groups (single blind): Group 1 with NLFC (SoundRecover) turned on after the first measurement time point (N = 13, age range 64 to 77 years, mean age = 70.31, SD = 5.19, one female, mean IQ = 106.31, SD = 9.82, two left-handed), and Group 2 with NLFC turned off (N = 13, age range 61 to 77 years, mean age= 70.38, SD = 4.27, four females, mean IQ = 105.23, SD = 17.73, two left-handed). Age and mean IQ were not different between the two groups (age: $t(24) = -.04$, $p = .97$, IQ: $t(24) = .19$, $p = .85$). Intelligence was measured using the KAI test (Kurztest für die Basisgrösse allgemeiner Intelligenz (Lehrl, 1992). Three participants had to be excluded from further analyses because of dropout from the study during the longitudinal assessment and one because of EEG artifacts (eye blinks every second).

At each measurement time point, we also assessed how many hours on average per day the participants had been wearing their hearing aids since the last measurement time point by analyzing the hearing aid logfiles. We could not find any differences between the two hearing aid groups in the average daily usage hours (the repeated measure ANOVA with the factors measurement time point and group for average daily usage hours did not reveal any significant results for a main effect of measurement time point (F(1.39,30.51)=2.89, p=.088), main effect of group (F(1,22)=.64, p=.433) or interaction (F(1.39,30.51)=.44, p=.577)). Table 1 provides an overview of the mean and standard deviation of the average daily usage hours for each group and measurement time point.

In addition, a control group of older adults with age-appropriate hearing (NHO) was recruited (N = 13, age range 62 to 76, mean age = 69.23, SD = 3.94, 5 females, mean IQ = 102.92, SD = 17.55). Age and IQ were not different between NHO and the hearing-impaired (HI) groups (age: t(37) = .74, p = .46, IQ: t(37) = .55, p = .59). All participants but four were right-handed, as indicated by standard handedness questionnaires (Annett, 1970; Bryden, 1977). All participants were native German or Swiss German speakers (in each HI group there was one German speaker). They reported no history of present or past neurological, psychiatric, or neuropsychological disorders. In addition, they all denied the consumption of drugs, illegal medication, and the continuous use of blood-thinners. None of the participants suffered from chronic tinnitus.

The local ethics committee of the Canton Zurich approved the study, and written informed consent was obtained from all participants. Participants were paid for their participation.

2.2. Hearing

The two moderately hearing-impaired groups (NLFC on and NLFC off) were tested regarding their pure-tone thresholds by a hearing care professional (see Figure 1). They were tested using an Aurical Plus audiometer (GN otometrics) with headphones (Telephonics TDH39), whereas the NHO group underwent testing with the Maico ST20 Audiometers (Maico Diagnostic GmbH, Berlin, Germany: http://www.maico-diagnostic.com/). Only hearing-impaired individuals who met the fitting range of the Phonak Ambra M H2O (between 15-75 dB hearing loss at 125 to 500 Hz, and between 25-90 dB hearing loss at 750-8000 Hz) were included in the study. All included participants exhibited a similar bilateral hearing acuity for the average of 0.5, 1, 2, 3, 4, 6, and 8 kHz (max. difference left and right ear < 15 dB HL). In addition, for the NHO participant group neither ear exceeded the threshold of > 30 dB HL for 0.5, 1, 2, 3, and 4 kHz. Furthermore, the required thresholds for 6 kHz tones were < 50 dB HL and for 8 kHz tones < 60 dB HL. The online hearing test Med-el, which is available at http://www.medel.com/de/online-hoertest/, was administered to the NHO group using the German version (Zokoll et al., 2012). This is an online digit triplet test that presents digit triplets in noise (Buschermöhle et al., 2014, 2015). Participants were required to recall three monosyllabic digits after having heard them presented through noise via headphones. The volume of the triplets varied adaptively in order to find the 50% intelligibility threshold of the triplets. Participants were to be excluded from the study if they had a higher signal-to-noise (SNR) ratio than 2.9 dB, however all tested participants passed. This test was developed as part of the European HearCom project (Vlaming et al., 2011).

2.3. Stimuli

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The nonsense syllables (logatomes) asa (/'a:sa/), ascha (/'a:ʃa/), and afa (/'a:fa/) from the phoneme perception test (Boretzki et al., 2011; Schmitt et al., 2015) were used in our study. This stimulus material had already been used in a previous study using EEG (Giroud et al., 2017). The alveolar /s/, the post-alveolar /sch/ and the labiodental /f/ were embedded in an initial and a final /a/ sound. The center frequency of the /:s/ was 7.65 kHz, of the /: ʃ/ was 3.14 kHz, and of the /:f/ was 11.03 kHz. These high-pitched fricatives were chosen because the NLFC algorithm specifically targets the rehabilitation of hearing in a high pitch range that is typically lost in adults with moderate age-related hearing loss. In order to create two equidistant intermediate acoustic stimuli between the two logatomes 'ascha' and 'asa', 'afa' and 'asa', and 'ascha' and 'afa' (see Figure 2), they were morphed (Zorn, 2000) in their aspects of pitch, energy, spectrum, and rhythm. Each of the three stimulus combinations were tested in a separate block (see experimental procedure). Block 1 contained the stimulus material with the stimulus pair ascha (/'a:ʃa/) and asa (/'a:sa/) and its two morphings, whereas in Block 2 the logatomes were replaced by ascha (/'a:ʃa/) and afa (/'a:fa/), and in Block 3 by afa (/'a:fa/) and asa (/'a:sa/). The first stimulus of each stimulus pair was used as the standard, while the second original stimulus and the two morphed stimuli served as deviants of different difficulty. The morphed stimulus with the weaker acoustic deviation from the standard was called Deviant 1 (DEV 1). The morphed stimulus with the stronger acoustic deviation from the standard was called Deviant 2 (DEV 2). The second original stimulus of each stimulus pair was used as Deviant 3 (DEV 3) and had the strongest acoustic distance from the standard stimulus (see Figure 3).

2.4. Longitudinal design

The two hearing-impaired groups had five sessions (M1-M5) during which EEG was measured. The NHO group attended only the first three appointments because we expected to find effects of repeated testing already at M2 or M3 due to the fact that they did not have to acclimatize to new hearing aids like the HI groups. The participants were invited for the first recording time point (M1), after which NLFC was turned on in the NLFC on group, and were then retested two weeks (M2), four weeks (M3), six weeks (M4) and at a follow up of 12 weeks (M5) after M1 (see Figure 2). Each participant's follow-up appointments were scheduled on the day of the week and the same time of day as their initial appointment to control for changes in attention during the day. Only one participant of the hearing-impaired group had to be re-scheduled at M3 and was tested one day later than usual, and one other participant of the NHO group was re-scheduled at M2 and was tested two days later than usual.

2.5. Experimental procedure

The experimental procedure had been established in a previous study (Giroud et al., 2017). During each measurement time point, participants were seated in a comfortable chair at a distance of about 75 cm in front of a speaker which was placed in front of a screen. Using a speaker instead of headphones was more applicable for hearing aid users. The speaker (KEF, HTS2001.2, 8 Ω) with the Uni-Q array technology was used to provide a single source of sound with a frequency range of 80 Hz – 27 kHz and a maximum output of 104 dB SPL. Before starting the EEG recording, the volume of a white noise sound was manually set to 65 dB using an audiometer (AL1 Acoustilyzer).

To avoid eye movement artifacts during EEG measurements, participants were instructed to fixate on the cross presented on the screen. Participants performed two runs of each of the three blocks, each lasting about nine minutes and followed by a short

pause. Their order was randomized between participants and between measurement time points. The standard stimulus was presented 540 times (p=0.75) during each block, while each deviant was presented 60 times (p=0.083) in a randomized order with an inter-stimulus interval of 730 ms. The Presentation software (www.neurobs.com; version 14.5) controlled the experiment. The task for participants was to listen to the stream of stimuli and to press the mouse button with the right index finger when a deviant stimulus was identified. Correct trials were averaged, resulting in a maximum of 60 trials per deviant and 540 trials for the standard stimulus. Before each EEG recording, participants were asked to set the volume level of the three original stimuli to an equal loudness level in 1 dB steps. If the volume was perceived differently by the participants, a jitter (a small deviation) in volume for the standard stimulus was introduced: A jitter of 1 dB (one third of stimuli 66 dB, one third of stimuli 64 dB, one third of stimuli with 65 dB) if the difference between the two stimuli was set to 1 dB, or a jitter of 2 dB if the difference between the two stimuli was set to 2 dB or more. The maximum perceived level difference between the stimuli was 2 dB. All stimuli were presented at a standardized volume of 65 dB SPL, except when the standard stimulus volume was jittered as described above. This procedure allowed participants to detect a deviant only by its perceived qualitative difference to the standard rather than by its perceived difference in loudness.

2.6. EEG recordings and preprocessing

By using the high-density Geodesic EEG system (Electrical Geodesics, Inc., USA) with 256 scalp electrodes, EEG was continuously recorded during each measurement time point. Impedances for all electrodes were kept below 30 kΩ. The data was online band-pass filtered between 0.1-100 Hz, while Cz served as the online reference. Offline, the data

was re-referenced to linked mastoids for visual inspection of the grand averages at electrode Cz, and afterwards to average references for further data analyses. The data was digitized at a sampling rate of 500 Hz. For the preprocessing steps, Brain Vision Analyzer Software (Version 2.0.4, Brainproducts, Munich, Germany) was used. First, the electrodes placed on the cheeks and on the neck were removed reducing the number of electrodes from 256 to 204. Second, the data was filtered offline between 0.1-20 Hz (24 dB/oct). An independent component analysis (ICA) was used to remove eye movements and eye blinks (Jung et al., 2000). Noisy channels were interpolated using topographic interpolation (Perrin et al., 1987) and amplitude changes higher than 100 µV were removed with a semi-automatic raw data inspection. After the data was clean, it was segmented into 1300 ms segments (from 100 ms pre-stimulus to 1200 ms post-stimulus) and baseline corrected relative to the 100 to 0 ms pre-stimulus time period. Only correct trials (when the deviant was successfully detected) were subjected to further EEG analyses. In the stimulus Block 1 with the stimuli Ascha-Asa, each participant with hearing impairment was able to identify at least 30 weak deviants (DEV 3) at each measurement time point, which allowed for the reliable calculation of the evoked activity (>30 correct trials for all measurement time points for each participant). In fact, for DEV 3 of the stimulus block Ascha-Asa, we were able to analyze on average 56.37 correct trials (min=30, max=60) at M1. We note here that for the following EEG analyses, we therefore focused only on the weak DEV 3 of the stimulus block Ascha-Asa, because not every hearing-impaired participant's performance was sufficiently accurate (<30 correct) DEV 1 and DEV 2 at M1 (Ascha-Asa DEV 1 min=0, max=9; Ascha-Asa DEV 2 min=2, max=56). These trials were averaged to compute the event-related potentials (ERPs) separately for each deviant and each measurement time point.

2.7. Microstates

Microstates can be compared statistically between groups and conditions using their mean GFP and the latency of the peak, for example. We used the hierarchical clustering algorithm AAHC (atomize and agglomerate hierarchical clustering) from the software Cartool (Version3.55, The Cartool community group, retrieved from https://sites.google.com/site/cartoolcommunity/) to identify the stable topographies across all grand averaged data (Brunet et al., 2011; Murray et al., 2008). To this end, we calculated the difference waves. Each data point of the grand averaged difference waves - separately from the five measurement time points for the two hearing-impaired groups and the three measurement time points for the NHO group - was treated as one cluster. Some clusters were then randomly selected and spatially correlated to the remaining clusters of the data set. Each template usually yields the highest correlation coefficient for several consecutive time points, and we specified that all unstable maps shorter than 20 ms were to be rejected. We then averaged all clusters that reached the highest spatial correlation at a specific time interval. The resulting averaged cluster formed the new template map for that group. Within each group, the clusters with the lowest global explained variance (GEV) were then identified and reassigned to the clusters with the highest correlation to the new map. In order to identify the optimal number of clusters for this step, we applied the Krzanowski-Lai (KL) criteria (Krzanowski and Lai, 1988; Murray et al., 2008). For fitting the clusters back to the individual data, we calculated the spatial correlation of the clusters with the individual subject data (Brunet et al., 2011; Murray et al., 2008). As dependent parameters, we obtained the mean GFP and the latency of the peak GFP of all microstates. With these obtained parameters, we then computed a one-way ANOVA to check for baseline differences at M1 between groups, at which both hearing-impaired groups had NLFC off. Thus, we did not expect HI group differences at M1 and considered M1 as a baseline to make sure that the two HI groups

do not differ in neurophysiological processing of the stimulus material. Further, in order to investigate longitudinal group differences, repeated measures ANOVA with the within-subject factor *measurement time point* (M2, M3) and the between-subject factor *group* (NLFC on, NLFC off, NHO) were calculated for the microstate parameters. In addition, repeated measures ANOVA with only *measurement time point* (M4, M5) as a within-subject factor and with *group* (NLFC on, NLFC off) as a between-subject factor were calculated separately for the microstate parameters. The Greenhouse–Geisser correction (Greenhouse and Geisser, 1959) was applied when the assumption of sphericity was violated, and pairwise t-tests corrected for multiple comparisons were used as post-hoc tests. Two-tailed p-values are reported throughout. The alpha level for all statistical analyses was set to $\alpha = 0.05$. Effect sizes are indicated by partial eta-squares (η^2_p).

2.8. P50, N1, and P2 peak detection

The microstate analysis did not reveal distinct microstates for the P50, the N1, and the P2 (see 3.2). This constraint notwithstanding, we assessed group and measurement time point differences in the P50, the N1, and the P2 in order to allow comparisons to previous studies in which P50, N1, and P2 peak amplitudes were assessed in hearing aid users (Bertoli et al., 2011; Billings et al., 2007, 2011; Easwar et al., 2015; Korczak et al., 2005; Marynewich et al., 2012; Miller and Zhang, 2014; Tremblay et al., 2006a, 2006b). Thus, we obtained AEP peak amplitudes and their respective latencies for the P50, N1, and P2 component for each participant and each measurement time point of the DEV 3 of the Ascha-Asa stimulus combination. The parameters were extracted at electrode Cz in order to directly compare the results to previous studies in which the amplitudes and latencies from electrode Cz were also obtained (Bertoli et al., 2011; Billings et al., 2007,

2011; Easwar et al., 2015; Korczak et al., 2005; Marynewich et al., 2012; Miller and Zhang, 2014; Tremblay et al., 2006a, 2006b). The peak latencies of the P50, the N1, and the P2 were classified in the grand average for each group and condition in order to define the latency bands for the amplitude and their respective latency extraction. According to this procedure, the maximum amplitude for the P50 was assessed in the interval of 50-150 ms after stimulus onset. For the N1, the interval of 100-200 ms after stimulus onset, and for the P2, the interval of 150-300 ms was chosen. The peaks were extracted individually in a semi-automatic procedure and confirmed by visual inspection. As with the microstate statistics, the amplitudes and latencies of the P50, N1, and P2 were then analyzed by means of a one-way ANOVA for baseline differences at M1, and with 2x3 (*measurement time point* (M2, M3) * *group* (NLFC on, NLFC off, NHO)) repeated measures ANOVA to assess the differences between hearing-impaired groups compared to NHO. Furthermore, we performed a 2x2 (*measurement time point* (M4, M5) * *group* (NLFC on, NLFC off)) repeated measures ANOVA to obtain the differences between the NLFC on and the NLFC off groups.

2.9. Analysis of behavioral data

The accuracy of the deviant detection and the mean reaction time (RT) for correct trials were computed for each of the three DEVs for each block, for each measurement time point, and for each participant. If the accuracy was below 20%, RTs were not calculated. This was the case for DEV 1 in all stimulus blocks (see Figure 3). Thus, RTs of DEV 1 were not included in the statistical analysis. Similar to the analysis of the microstates and the P50, N1, and P2 analysis, we calculated a one-way ANOVA to assess group differences at M1, and then a 2x3x3 (*measurement time point* (M2, M3) * deviant (DEV 1 (excluded for RT), DEV 2, DEV 3) * *group* (NLFC on, NLFC off, NHO)) repeated measures

ANOVA to assess the differences between hearing-impaired groups compared to NHO. This was followed by a 2x3x2 (*measurement time point* (M4, M5) * deviant (DEV 1 (excluded for RT), DEV 2, DEV 3) * *group* (NLFC on, NLFC off)) repeated measures ANOVA to assess the differences between the NLFC on and the NLFC off groups. Because we only analyzed EEG measures for the DEV 3 from stimulus block Ascha-Asa (see 2.6.), we calculated the ANOVAs separately for each stimulus block to allow a direct comparison between the EEG data and the behavioral data for the Ascha-Asa stimulus block.

The ANOVAs were followed by pairwise t-tests corrected for multiple comparisons by Bonferroni correction, when appropriate. We report all results for an alpha level below $\alpha = 0.05$. Effect sizes are indicated by partial eta-squares (η^2_p).

3. Results

Detailed descriptions are given of first, the behavioral performance and second, the microstates statistics. In the third part, the results of the AEPs, namely the P50, the N1, and the P2, are presented. In each of the three sections, there is a first part about baseline differences between the groups at M1, a second part about the differences between the hearing-impaired and those with normal hearing at M2 and M3, and a third part about the differences between the groups with the two distinct hearing aid features at M4 and M5.

3.1. Behavioral performance

3.1.1. Analyses for M1, M2, and M3 for all three groups and all deviants

3.1.1.1. Stimulus combination 1: Ascha-Asa

The one-way ANOVA for accuracy at M1 revealed group differences for DEV 1 (F(2,36)=9.48, p<.001) and DEV 2 (F(2,36)=11.88, p<.001), but not for DEV 3 (p>.05). For DEV 1 and DEV 2, post-hoc analysis showed that accuracy was higher for NHO compared to hearing-impaired (all p<.01). The 2 (M2, M3) * 3 (DEV 1, DEV 2, DEV 3) * 3 (NHO, NLFC on, NLFC off) repeated measures ANOVA further revealed that there was a main effect of measurement time point (F(1,36)=4.30, p=.04, η^2_p=.11) showing 3% increase of accuracy from M2 to M3 on average across all groups. The accuracy was higher for DEV 3 than DEV 2 (p<.001) and for DEV 2 than DEV 1 (p<.001) as was shown in the main effect deviant (F(2,72)=199.06, p<.001, η^2_p=.85). Further, the main effect group (F(2,36)=19.43, p<.001, η^2_p=.52) showed that NHO performed 23.8% better than the group with NLFC off (p<.001) and 25.8 % better than the group with NLFC on (p<.001) averaged across both measurement time points. The interaction deviant * group (F(3.46,62.25)=8.35, p<.001, η^2_p=.32) showed that the NHO group performed better than the hearing-impaired, especially in the difficult deviant condition, DEV 1.

For RT, the one-way ANOVA at M1 showed that RT was different between groups for DEV 2 (F(2,36)=10.21, p<.001), but not DEV 3 (p>.05). More precisely, it revealed that NHO performed faster than the two hearing-impaired groups (both p<.01) in the DEV 2 condition. The 2 (M2, M3) * 2 (DEV 2, DEV 3) * 3 (NHO, NLFC on, NLFC off) repeated measures ANOVA showed a significant main effect of deviant (F(1,36)=142.41, p<.001, η^2_p=.80), a significant main effect of group (F(2,36)=8.52, p=.001, η^2_p=.32), and a significant interaction of deviant * group (F(2,36)=8.35, p<.001, η^2_p=.36). The post-hoc tests for these effects revealed that participants detected the DEV 3 faster than the DEV 2 (p<.001) and that NHO performed faster than the two hearing-impaired groups (both p<.05). Further, the interaction showed that the NHO performed faster than the hearing impaired, especially in the DEV 2 condition.

In sum, these results show that all participants detected the deviants with stronger deviation to the standard faster and with higher accuracy and increased detection accuracy from M2 to M3. Furthermore, NHO performed with higher accuracy and faster times than the two HI groups, especially in the more difficult conditions.

3.1.1.2. Stimulus combination 2: Ascha-Afa

The one-way ANOVA for accuracy did not reveal any significant differences between groups at M1. The 2 (M2, M3) * 3 (DEV 1, DEV 2, DEV 3) * 3 (NHO, NLFC on, NLFC off) repeated measures ANOVA however showed that there was a significant main effect of measurement time point ($F(1,32)=4.46$, $p=.04$, $\eta^2_p=.12$) revealing that accuracy increased from M2 to M3 (2.6 %). Furthermore, the main effect deviant ($F(1.32,42.19)=238.35$, $p<.001$, $\eta^2_p=.88$) showed that DEV 3 was detected with higher accuracy than DEV 2 ($p<.001$) and DEV 2 was detected with higher accuracy than DEV 1 ($p<.001$).

For RT, the one-way ANOVA did not reveal any significant differences between groups at M1. The 2 (M2, M3) * 2 (DEV 2, DEV 3) * 3 (NHO, NLFC on, NLFC off) repeated measures ANOVA for RT further showed that there was a significant main effect of measurement time point ($F(1,35)=12.11$, $p=.001$, $\eta^2_p=.26$), a significant main effect deviant ($F(1,35)=137.79$, $p<.001$, $\eta^2_p=.80$) and an interaction between deviant * group ($F(2,35)=3.81$, $p=.03$, $\eta^2_p=.18$). Irrespective of group, the RT was shorter at M3 than M2 (22.02 ms) and DEV 3 was detected faster than DEV 2 (74.95 ms). The interaction revealed that the NHO group showed specifically faster RT as compared to the two hearing-impaired groups when detecting the easier DEV 3.

Similar to the stimulus combination Ascha-Asa, all participants increased accuracy from M2 to M3, and the deviants with stronger deviation to the standard were detected faster

and with higher accuracy. However, contrary to the stimulus combination Ascha-Asa, in this stimulus combination Ascha-Afa, there were no group effects and no group interactions found for accuracy, while there was a decrease of RT from M2 to M3 which was not evident in the stimulus combination Ascha-Asa.

3.1.1.3. Stimulus combination 3: Afa-Asa

The one-way ANOVA at M1 for accuracy showed a significant main effect of group (for DEV 1: $F(2,35)=8.20$, $p=.001$, for DEV 2: $F(2,36)=7.14$, $p=.002$, for DEV 3: $F(2,35)=3.86$, $p=.03$) for each DEV. Post-hoc t-tests revealed that the NHO performed better than the two hearing-impaired groups for DEV 1 (both $p<.05$) and DEV 2 (both $p<.05$), while for DEV 3 there was only a trend (both $p<.01$). The 2 (M2, M3) * 3 (DEV 1, DEV 2, DEV 3) * 3 (NHO, NLFC on, NLFC off) repeated measures ANOVA showed a main effect of deviant ($F(1.12,38.09)=81.34$, $p<.001$, $\eta^2_p=.71$), which revealed that DEV 3 was detected with higher accuracy than DEV 2 ($p<.01$) and DEV 2 with higher accuracy than DEV 1 ($p<.001$). The significant main effect group ($F(2,34)=8.10$, $p=.001$, $\eta^2_p=.32$) further showed that the NHO performed better than the two hearing-impaired groups ($p<.01$). Moreover, there was a significant interaction between deviant and group ($F(2.24,38.09)=4.76$, $p=.01$, $\eta^2_p=.22$) showing that NHO performed better especially under difficult conditions such as detecting DEV 1.

For RT, the one-way ANOVA at M1 revealed a main effect of group for both DEV 2 and DEV 3 (DEV 2: $F(2,36)=4.63$, $p=.02$, DEV 3: $F(2,35)=4.41$, $p=.02$). The post-hoc t-tests further showed that for both DEV 2 and DEV 3, NHO performed faster than the group with NLFC on (both $p<.05$). The 2 (M2, M3) * 2 (DEV 2, DEV 3) * 3 (NHO, NLFC on, NLFC off) repeated measures ANOVA resulted in a main effect of measurement time point ($F(1,36)=5.29$, $p=.03$, $\eta^2_p=.13$) leading to the conclusion that RT decreased from M2 to

M3 irrespective of group or deviant. Further, the main effect deviant (F(1,36)=6.79, p=.01, η^2_p=.16) revealed that DEV 3 was detected faster than DEV 2. In addition, there was a main effect of group (F(2,36)=7.75, p=.002, η^2_p=.30) showing that the NHO performed faster than both hearing-impaired groups (both p<.05). The interaction between deviant and group (F(2,34)=3.66, p=.04, η^2_p=.17) and the threefold interaction measurement time point * deviant * group (F(2,36)=4.76, p=.02, η^2_p=.21) further showed that NHO performed faster than the hearing-impaired especially when detecting DEV 2 (the more difficult deviant) and that this difference was greater at M2 than M3. Similar to the results in the other two stimulus combinations, all participants detected the deviants with strong acoustic deviation to the standard faster and with higher accuracy. However, in this stimulus combination there was no increase of accuracy from M2 to M3 like in the other two stimulus combinations, only a decrease of RT (as seen in the combination Ascha-Afa). The NHO also performed better (similar to Ascha-Asa stimulus combination) and faster (similar to Ascha-Afa stimulus combination) compared to the HI groups, especially in the difficult conditions.

3.1.2. Analyses for M4 and M5 for the two HI groups and all deviants

3.1.2.1. Stimulus combination 1: Ascha-Asa

The 2 (M4, M5) * 3 (DEV 1, DEV 2, DEV 3) * 2 (NLFC on, NLFC off) repeated measures ANOVA for accuracy showed a main effect deviant (F(1.18,28.4)=270.48, p<.001, η^2_p=.92). The post-hoc t-tests pointed to the higher accuracy for DEV 3 compared to DEV 2 (p<.001) and the higher accuracy for DEV 2 compared to DEV 1 (p<.001). The interaction measurement time point * group (F(1,24)=5.17, p=.03, η^2_p=.18) showed that the group with NLFC on showed a stronger increase of accuracy from M4 to M5 compared to the group with NLFC off, which is also evident in the post-hoc t-test

comparing the increase of accuracy from M4 to M5 irrespective of deviant between the group with NLFC on and the group with NLFC off (p=.032).

The corresponding ANOVA for RT resulted in a significant main effect of measurement time point (F(1,24)=4.54, p=.04, η^2_p=.16) and significant main effect deviant (F(1,24)=110.45, p<.001, η^2_p=.82). At M4 the two groups exposed shorter RTs than at the follow-up measurement time point M5 (13.12 ms) and RTs were shorter when detecting DEV 3 compared to DEV 1 (105.37 ms).

In sum, these results show that stronger acoustic differences were detected faster and with higher accuracy in both groups. The group with NLFC on showed a stronger accuracy increase from M4 to M5, while RT increased from M4 to M5 in all participants.

3.1.2.2. Stimulus combination 2: Ascha-Afa

For accuracy, the 2 (M4, M5) * 3 (DEV 1, DEV 2, DEV 3) * 2 (NLFC on, NLFC off) repeated measures ANOVA only revealed a significant main effect of deviant (F(1.48,32.55)=191.09, p<.001, η^2_p=.90) showing that accuracy was higher for DEV 3 compared to DEV 2 (p=.001) and for DEV 2 compared to DEV 1 (p<.001).

The same ANOVA for RT (without DEV 1) also resulted in a significant main effect of deviant (F(1,24)=44.20, p<.001, η^2_p=.65), and a significant main effect of measurement time point (F(1,24)=4.29, p=.049, η^2_p=.15) with lower RT at M4 compared to M5 (15.83 ms). In addition, DEV 3 was detected faster than DEV 1 (58.14 ms).

Similarities in the results to stimulus combination Ascha-Asa included faster and more accurate detection of the stronger acoustic differences, and an increase of RT from M4 to M5, irrespective of group. However, in this stimulus combination (Ascha-Afa) there was no evidence of a stronger increase of accuracy from M4 to M5 in the group with NLFC on as compared to the group with NLFC off.

3.1.2.3. Stimulus combination 3: Afa-Asa

The 2 (M4, M5) * 3 (DEV 1, DEV 2, DEV 3) * 2 (NLFC on, NLFC off) repeated measures ANOVA for accuracy only revealed a significant main effect deviant (F(1.16,25.45)=89.66, p<.001, η^2_p=.80) confirming that DEV 3 was detected with higher accuracy than DEV 2 (p=.02) and DEV 2 with higher accuracy than DEV 1 (p<.001), respectively.

For RT, 2 (M4, M5) * 2 (DEV 2, DEV 3) * 2 (NLFC on, NLFC off) repeated measures ANOVA showed a main effect measurement time point (F(1,24)=4.96, p=.04, η^2_p=.17) and a main effect deviant (F(1,24)=17.37, p<.001, η^2_p=.42). From M4 to M5 the reaction times decreased. Across the two measurement time points, DEV 3 was detected faster than DEV 2.

Comparable to the other two stimulus combinations, stronger acoustic differences were detected faster and with higher accuracy, but unique to this stimulus combination was a decrease of RT from M4 to M5 across groups.

3.2. Microstates

For the DEV 3 trials, the topographic AAHC clustering revealed a total of 14 temporally stable maps over the ERP time course from 0-1200 ms as the best solution, which explained 63.81% of the global variance. For further analysis, we chose the three maps that each explained at least 10% of the total variance (see Figure 5): Map 1, corresponding to the N2b, accounted for 47% of the variance; Map 2, which is related to the frontal P3b, accounted for 10%; and Map3, corresponding to the parietal N3b, explains 24%. If a map did not occur in a participant, it was coded as a missing value.

The three maps were subjected to further analyses, namely a re-fitting to single subject's data from 0 -1200 ms after stimulus onset.

3.2.1. Analyses for M1, M2, and M3 to compare all three groups

3.2.1.1. Mean GFP

The one-way ANOVA for M1 did not reveal any significant group differences. However, for the N2b-like mean GFP, the repeated measures ANOVA (measurement time point (M2, M3) * group (NLFC on, NLFC off, NHO)) revealed a main effect of group ($F(1,29)=7.03$, $p=.003$, $\eta^2_p=.33$), showing that the NHO had lower GFP at M2 and M3 than the group with NLFC off ($p=.002$), while the group with NLFC on was not different from the other two groups (both $p>.05$). The repeated measures ANOVA for the mean GFP of the frontal P3b-like microstate did not reveal any significant results. The analysis for the mean GFP of the parietal P3b showed, similar to the N2b-like microstate, a main effect of group ($F(2,36)=3.97$, $p=.028$, $\eta^2_p=.18$) revealing that the NHO had lower GFP at M2 and M3 compared to the group with NLFC off ($p=.024$), while the group with NLFC on was not different from the other groups (both $p>.05$). See Figure 5 for changes in the mean GFP of all microstates analyzed here.

3.2.1.2. Latency of peak GFP

The one-way ANOVA for M1 did not reveal any significant group differences in the latency of the peak GFP for the three microstates. Neither did we find any modulations across measurement time points for the latency of the peak GFP of the three microstates.

3.2.2. Analyses for M4 and M5 to compare the two HI groups

3.2.2.1. Mean GFP

The repeated measures ANOVA (measurement time point (M4, M5) * group (NLFC on, NLFC off)) for the mean GFP of the N2b-like microstate did not reveal any significant differences. The analysis for the frontal P3b-like microstate showed that there was a main effect measurement time point ($F(1,18)=41.26$, $p<.001$, $\eta^2_p=.70$), revealing that the mean GFP of the frontal P3b-like microstate decreased from M4 to M5. Further, there was an interaction of measurement time point * group ($F(1,18)=5.26$, $p=.03$, $\eta^2_p=.23$), showing that the decrease of the mean GFP of the frontal P3b-like microstate was stronger for the group with NLFC on compared to the group with NLFC off, as the post-hoc t-test between the group with NLFC on and the group with NLFC off also suggested ($p=.034$). Additionally, the mean GFP of the parietal P3b-like microstate also decreased from M4 to M5 ($F(1,20)=7.91$, $p=.01$, $\eta^2_p=.28$), but there was no measurement time point * group interaction.

3.2.2.2. Latency of peak GFP

For the latency of the peak GFP, we found no significant modulations.

3.2.3. Comparison of time points

The ANOVA results of the mean GFP showed that at M2 and M3 the mean GFP for the group with NLFC off was higher compared to the NHO for both the N2b-related and the parietal P3b-related microstates. At the same time, the ANOVA results comparing the two HI groups suggest that the mean GFP of the frontal and the parietal P3b-like microstates decreased from M4 to M5. It is therefore possible that at M5 the mean GFP of the parietal P3b-related microstate of the group with NLFC off is not different from the mean GFP of the P3b-related microstate of the NHO group at M3 because of the decrease of mean GFP from M4 to M5. This could indicate a delayed plasticity effect in the HI group with NLFC off as the NHO group shows a faster decrease of mean GFP

across the measurement time points (and therefore a faster decrease of processing effort) than the group with NLFC off, which shows a decrease of mean GFP to a similar level as the NHO group only at M5. In order to test this assumption, we compared the mean GFP of the parietal P3b-like microstate of the HI group with NLFC off at M5 with the mean GFP of the parietal P3b-like microstate of the NHO group at M3. As expected, we did not find any significant differences ($t(23)=-.26$, $p=.795$).

3.3. P50, N1, P2 peak amplitude results

The ERPs from electrode Cz for the easy deviant DEV 3 of the stimulus combination Ascha-Asa are depicted in Figure 6, and the descriptive data of the peak and latency of the P50, the N1, and the P2 are described in Table 2.

3.3.1. Analyses for M1, M2, and M3 to compare all three groups

The one-way ANOVA for M1 showed that there was a main effect of group for the P50 latency ($F(2,36)=3.73$, $p=.03$) and for the N1 latency ($F(2,36)=28.13$, $p<.001$) revealing that the NHO displayed shorter P50 latencies as compared to the group with NLFC off ($p<.05$) and shorter N1 latencies as compared to both hearing-impaired groups (both $p<.001$). The repeated measures ANOVA (measurement time point (M2, M3) * group (NHO, NLFC on, NLFC off) for the P50 revealed a significant interaction ($F(2,36)=3.97$, $p=.03$, $\eta^2_p=.18$) showing that for the group with NLFC off and the NHO there was a decrease of amplitude from M2 to M3, while for the group with NLFC on, there was an increase. For the P50 latency there was a main effect of group ($F(2,36)=4.37$, $p=.02$, $\eta^2_p=.20$) revealing that across M2 and M3, the P50 latency was longer for the hearing-impaired compared to the group with normal hearing ($p<.05$). The repeated measures ANOVA for the N1 amplitude resulted in a significant effect of measurement time point ($F(1,36)=5.05$, $p=.03$, $\eta^2_p=.12$) showing that irrespective of group, the amplitude

increased from -2.84 to -3.47 μV. For the N1 latency, there was another main group effect ($F(2,36)=9.59$, $p<.001$, $\eta^2_p=.35$) similar to the P50 latency, showing that NHO had shorter latencies than both hearing impaired groups (both $p<.01$). For the N2 latency and amplitude there were no significant effects.

3.3.2. Analyses for M4 and M5 to compare the two HI groups

The analysis for the P50, N1, and P2 amplitudes and latencies did not reveal any significant effects.

4. Discussion

In this paper, we examined longitudinal modulations of early sensory-driven and later cognitive-related auditory processing and their modulations by hearing loss and hearing aid treatment in healthy, older adults. Traditionally, studies have investigated the effects of hearing aid amplification at only the initial stages of hearing, namely for the P50, N1, and the P2 in young adults (Billings et al., 2007, 2011; Marynewich et al., 2012; Miller and Zhang, 2014; Tremblay et al., 2006a) or with older adults using cochlear implants and other implants (e.g., Schierholz et al., 2017). Decreases or increases in amplitudes and longer latencies in aided when compared to unaided situations are usually reported (Billings et al., 2011, 2007; Marynewich et al., 2012; Miller and Zhang, 2014; Tremblay et al., 2006a). The direct investigation of auditory plasticity in an older age group, the group most affected by presbycusis, ensures the applicability of the study results in the clinic. In addition, the research design of repeated EEG lab testing over a three month period of both older adults with age-appropriate hearing as well as those who use hearing aids made it possible to describe auditory plasticity. During these three months, hearing-impaired participants were required to have their hearing aids switched on in their everyday life for at least eight hours each day. Furthermore, all participants had at

least one year's hearing aid experience, which minimized the potential biases involved when experiencing a hearing aid for the first time. We follow with a comprehensive discussion of the results and their implications.

4.1. Delayed auditory plasticity in hearing-impaired compared to normal-hearing older adults

Previous studies have demonstrated differences in auditory cortical representations in aided compared to unaided listening conditions (Bertoli et al., 2011; Billings et al., 2011; Marynewich et al., 2012; Tremblay et al., 2006a) when participants were passively presented with auditory stimuli. In the present study, the participants actively listened to speech syllables while performing a deviant detection task. This task evokes not only early AEPs, but also the later occurring N2b and the P3b event-related component, which allows for the study of longitudinal plasticity in both early auditory processing and also cognitive-related auditory processing as a function of hearing loss. In line with previous studies (Korczak et al., 2005; Marynewich et al., 2012; Miller and Zhang, 2014) and in accordance with our hypothesis, there were no group differences in the P50, N1, and P2 peak amplitudes between hearing aid users and normal-hearing listeners. Furthermore, at M1, there were no significant group differences in the GFP of the N2b-like, the P3b-like and the LPP-like microstates. Instead, and in line with our hypothesis, we found slightly longer latencies in hearing aid users compared to normal-hearing older adults in the P50 and the N1 across the first three measurement time points, as was also shown in previous within-subject studies with younger adults (Marynewich et al., 2012; Miller and Zhang, 2014). This delay in the early cortical processes has partially been attributed to the time consumed by signal processing in the hearing aids, which takes about 4.5 ms (Miller and Zhang, 2014) and leads to a total delay of approximately

10 ms in the brain. These delays could not be found in the later P2 peak latency, or in the N2b-like or P3b-like microstates GFP peak latencies. In other words, it appears that the delay of the initial perceptual processing did not affect later cognitive processing. Furthermore, previous within-subject studies have reported that behavioral RTs are shorter in aided compared to unaided listening situations in the hearing-impaired (Downs, 1982; Gatehouse and Gordon, 1990), which means that in total, the latency delay of early AEPs occurring due to the signal processing time, does not reverse the hearing aids' overall effect, namely a decrease in behavioral RT.

Differences in RTs between aided and unaided conditions have also been related to (listening) effort (Downs, 1982; Gatehouse and Gordon, 1990). For example, it was shown that reaction times and therefore the (listening) effort was decreased in hearing-impaired individuals with the use of hearing aids (Downs, 1982; Gatehouse and Gordon, 1990). However, it is debatable whether higher performance always reflects less listening effort. For example, other studies also reported more subjective effort in older hearing aid users in speech recognition tasks with modulated noise compared to tasks with steady state noise, even though the participants performed better in the task with modulated noise (Rudner et al., 2012). In this between-subject design, we found longer RTs in the hearing-impaired compared to the normal-hearing older adults when they correctly identified deviant stimuli. This finding confirms previous results which demonstrated that unaided poorer listeners show longer RTs in an auditory n-back task compared to unaided better listeners (Frtusova and Phillips, 2016). This was considered to be an effect of higher perceptual demand and therefore higher perceptual effort in the group with poorer hearing (Frtusova and Phillips, 2016). The assumption that higher perceptual effort leads to longer RTs in the older hearing-impaired is further supported by the finding that these RT delays are modality specific and are not found in

the visual domain (Frtusova and Phillips, 2016). In addition, we matched our three experimental groups in IQ as measured by the KAI test (Lehrl, 1992), which incorporates visual processing speed as a subtest. This further promotes the interpretation that the longer RTs reflect higher perceptual demand specific to the auditory domain. In general, the lower accuracy in the group with hearing impairment also suggests that perceptual demand was higher for the hearing-impaired compared to those with normal hearing.

The other core research focus of this work was to evaluate the possible differences in longitudinal auditory plasticity between the hearing-impaired with NLFC off and those with normal hearing. Behaviorally, all groups increased in accuracy and decreased in RT with repeated testing reflecting a decrease in perceptual effort. However, the electrophysiological data showed that in the normal-hearing group the GFP of the cognitive N2b-like and P3b-like microstates at measurement time point two (after two weeks) decreased, while the GFP was higher in the hearing-impaired group with NLFC off at M2 and M3. This finding could suggest lower auditory plasticity in the hearing impaired-group compared to the normal-hearing group. The rationale behind this is that, with repeated testing, it is expected that the task will get easier and therefore require less effort. Less required effort should result in a decrease of brain activation as a function of the fewer neural resources needed to perform the task. Here, we used GFP of microstates as a reflection of the global brain activation during two distinct neural processes: First, the auditory categorization of a deviant stimulus as flagged by the N2b-like microstate (Näätänen and Gaillard, 1983; Simson et al., 1977), and second, memory updating (Debener et al., 2002; Kok, 1997; Polich, 2007; Volpe et al., 2007) as reflected in the P3b-like microstate. In other words, we argue that the delayed decrease of activation strength in both of these microstates in the hearing-impaired with NLFC off is

correlated with a delayed decrease of (perceptual) effort during auditory categorization and memory updating as evidenced by the diminishing difference in GFP at M5. To date, several behavioral studies have shown that hearing aids can decrease processing effort in auditory tasks when compared to unaided conditions (Hällgren et al., 2005; Hornsby, 2013; Rudner, 2016; Tremblay and Backer, 2016). The present study supports these findings by providing neurophysiological evidence that the hearing-impaired not only immediately show higher processing effort, but that they also need more exposure to auditory stimuli after being fitted with a new hearing aid algorithm to decrease their processing effort across time.

Several behavioral studies have so far used auditory cognitive measures as outcome variables when comparing aided to unaided listening situations in older adults. For example, performance in working memory, as assessed by the auditory reading span test, was higher when participants were aided (Doherty and Desjardins, 2015). Furthermore, hearing aid users improved in dichotic listening tasks after eight weeks of being exposed to the acoustic environment through the hearing aid, while controls did not (Lavie et al., 2015). These findings suggest that hearing aids facilitate perceptual auditory processes leading to benefits in cognitive-related auditory tasks. For the purpose of better understanding possible hearing aid benefits in cognitive-related auditory processing, we assessed not only early perceptual evoked-potentials such as the P50, N1, and P2, but also the auditory N2b/P3b event-related potentials as markers for cognitive-related auditory processing. The N2 has been described as a neural marker for the auditory categorization of phonetically deviant stimuli (Näätänen and Gaillard, 1983; Simson et al., 1977) and the P3 as a neural marker for attention and memory updating (Debener et al., 2002; Kok, 1997; Polich, 2007; Volpe et al., 2007).

Interestingly, the studies described above have linked the cognitive benefits of hearing aids to lower cognitive effort (Doherty and Desjardins, 2015). Other research has also shown that hearing aids reduced the extra cognitive effort needed to successfully understand speech (Desjardins and Doherty, 2013, 2014). In an attempt to better define cognitive effort in the context of speech processing, we used the term processing effort to describe the additional resources allocated to the auditory task in order to meet the task requirements (Lemke and Besser, 2016). Furthermore, the authors describe "brain over-activation" as a potential neural correlate for higher processing effort (Lemke and Besser, 2016). Thus, in this study we obtained the GFP of the event-related potentials to serve as a global measure for brain activation and therefore also as a correlate of processing effort.

4.2. Acclimatization to specific hearing aid feature takes several weeks

As a third research question, we intended to test different hearing aid features against each other regarding their effect on auditory plasticity. We predicted that NLFC would increase performance in hearing-impaired older adults more strongly than pure amplification across the three months of study duration (Alexander, 2016; Wolfe et al., 2011, 2015). Taking into consideration the results of several studies which found that some hearing aids decreased processing effort (Hällgren et al., 2005; Hornsby, 2013; Rudner, 2016; Tremblay and Backer, 2016), we further hypothesized that NLFC would reduce processing effort of high pitched fricatives more strongly than pure amplification by increasing audibility of fricatives. In this study, we found a stronger increase of accuracy from M4 to M5 in the group with NLFC on compared to the group with NLFC off in the stimulus block Ascha-Asa (the same from which the EEG data was processed), although the two groups improved their performance across time. Previous studies also

found behavioral improvements across several months of using NLFC, namely decreases in the thresholds for the correct identification of syllables (Wolfe et al., 2011, 2015). Notably, it is difficult to attribute these effects solely to the use of NLFC because these studies neglected to collect control group data. Interestingly, in our study, we found a similar interaction in the neurophysiological data, namely a stronger decrease of GFP of the P3b-like microstate (a flag for a decrease of processing effort) in the group with NLFC on. Furthermore, we found a higher GFP in the N2b-like and the parietal P3b-like microstate in the normal-hearing group compared to the group without NLFC at measurement time points two and three, while the group with NLFC did not differ significantly from the other two. Interpreting the differences in GFP again in the framework of processing effort (as described in the previous section) (Lemke and Besser, 2016) leads to the conclusion that the group without NLFC demonstrated higher processing effort than the normal-hearing group, while the group with NLFC did not differ in terms of processing effort from the normal-hearing group. This means that the improvement of audibility of the fricatives provided by the NLFC algorithm decreases the processing effort of these fricatives. The second set of differences in the neurophysiological parameters found was in line with our predictions, namely that the brain needed several weeks to acclimatize to a new hearing aid feature. This was indicated by the differences in GFP between the group with NLFC on compared to NFLC off only at measurement time point five in the frontal P3b-like microstate. Based on this finding, we conclude that an older brain over the age of 60 years needs more time than hitherto expected to adapt to a new hearing aid feature.

4.3. Limitations

The current study design did not allow for the complete disentanglement of the sole effects of hearing aid acclimatization from the sole effects of hearing loss on auditory plasticity. To do this, we would have needed an additional control group, namely a group with moderate hearing loss, which would have remained untreated during the study period of three months. We agreed that this would have been an unethical study procedure.

Furthermore, future use of the paradigm could be optimized to also look at differences in more difficult deviants, which would be possible when using more trials per condition. However, such optimization would mean that the tasks would take longer to perform, which is not feasible for older study participants.

4.4. Conclusions

Through the application of a longitudinal EEG approach, we examined auditory plasticity in two hearing-impaired groups using different hearing aid features, and in normal-hearing healthy older adults. Compared to previous studies which investigated the effect of hearing aids in normal-hearing younger adults (Billings et al., 2007, 2011; Marynewich et al., 2012; Miller and Zhang, 2014; Tremblay et al., 2006a), our findings are applicable to an older population, the one that suffers most from age-related hearing loss. The novel result of this study is that the hearing-impaired, especially the group with NLFC off, demonstrated higher auditory processing effort (as indicated by the higher GFP in the N2b and P3b) and an accordingly delayed cognitive-related auditory plasticity when compared to those with normal hearing. In other words, the hearing-impaired individuals needed more exposure to the auditory stimulus material in order to decrease the electrophysiological activity that flags processing effort. In general, we also demonstrated that low-level auditory treatment which is meant to improve

auditory perception additionally provides a scaffolding to buttress higher cognitive functioning. This interpretation receives cardinal support by the GFP differences of the P3b between the group with NLFC on compared to the group with NLFC off. In our view our data add strong credence to the view that low-level auditory treatment improves perception which in turn may release cognitive resources or increase cognitive spare capacity. It is not cognition as such that is improved but the resources available for cognitive processing. An additional note to this context is that at least twelve weeks are required for an older brain to adapt to such a new hearing environment.

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Table Descriptions

Table 1:

Means and standard deviations of the average daily usage hours of the hearing aids are shown by group and measurement time point. T-statistics show no group differences for the different measurement time points.

	Group	M	SD	
M1-M2	NLFC on	12.58	4.02	
	NLFC off	11.14	4.70	t(23)=.86, p=.40
M2-M3	NLFC on	13.16	2.31	
	NLFC off	13.00	1.80	t(24)=.75, p=.46
M3-M4	NLFC on	14.01	1.61	
	NLFC off	13.25	1.36	t(23)=1.35, p=.19
M4-M5	NLFC on	13.18	2.61	
	NLFC off	13.00	1.31	t(24)=.94, p=.36

Note M= Mean, SD = Standard Deviation

Table 2:
Means and standard deviations of P50, N1 and P2 amplitudes and latencies derived from electrode Cz, separately for each group and measurement time point.

	Group	P50 Latency		P50 Amplitude		N1 Latency		N1 Amplitude		P2 Latency		P2 Amplitude	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
M1	NLFC on	103.54	18.94	2.88	1.34	161.85	7.89	-3.35	1.74	262.46	20.30	3.80	2.07
	NLFC off	109.08	9.15	2.81	1.37	159.23	7.73	-2.89	2.97	273.23	34.76	3.62	1.54
	NHO	92.77	16.62	2.19	1.11	139.69	9.01	-2.83	1.61	258.15	36.46	3.57	2.14
M2	NLFC on	107.54	16.68	2.14	1.24	161.54	16.64	-3.01	1.57	272.31	33.76	3.56	1.42
	NLFC off	99.54	18.76	2.23	1.31	160.00	12.06	-3.02	2.38	268.31	29.27	3.47	1.75
	NHO	92.00	15.10	2.44	0.94	144.92	13.33	-2.48	2.12	252.00	45.02	3.42	1.88
M3	NLFC on	109.08	5.51	2.81	1.53	158.46	8.76	-3.85	2.07	267.23	27.73	3.70	2.04
	NLFC off	104.00	21.69	1.80	1.07	159.23	14.62	-3.09	3.43	255.38	24.80	3.36	2.35
	NHO	95.08	17.14	1.63	1.35	142.77	8.93	-3.46	2.47	244.92	29.32	3.30	2.79
M4	NLFC on	94.46	24.90	2.75	1.67	162.46	6.44	-3.67	2.14	272.31	36.04	2.89	1.32
	NLFC off	102.00	22.23	2.47	1.27	156.77	18.66	-2.74	3.08	264.15	27.25	3.39	2.67
M5	NLFC on	107.54	16.58	1.78	1.06	161.85	13.89	-3.62	2.30	267.85	29.48	2.58	1.16
	NLFC off	106.15	8.22	2.59	1.66	159.23	14.93	-3.27	3.54	274.77	29.99	3.34	2.84

Note M= Mean, SD = Standard Deviation

Figure Legends

Figure 1:
Audiogram of the normal-hearing older group (NHO), the moderately hearing-impaired group using NLFC (NLFC on) and the moderately hearing-impaired group having NLFC turned off in their hearing aid (NLFC off).

Figure 2:
The combination of the stimulus material for the three different stimulus blocks. Embedded between an initial and a final /a/ sound were the alveolar /s/, the post-alveolar /sch/ and the labiodental /f/. Two equidistant intermediate acoustic stimuli between the two logatomes 'ascha' and 'asa', 'afa' and 'asa', and 'ascha' and 'afa' were created by morphing (Zorn, 2000) in their aspects of pitch, energy, spectrum, and rhythm.

Figure 3:
This Figure depicts the spectrogram of the stimulus material (top row), and the behavioral data, namely the deviant detection rate (middle row) and the reaction times

(lowest row) for each stimulus and for each measurement time point (M1, M2, M3, M4, and M5). A) depicts the results for the stimulus block 1 with /Ascha/ as a standard stimulus, and /Asa/ as the easy deviant DEV 3 with DEV 1 and DEV 2 two equidistant morphings between standard stimulus and DEV 3. B) shows stimulus block 2 with the standard stimulus /Ascha/ and DEV 3 /Afa/ together with the two morphings. C) shows stimulus block 3 with the standard stimulus /Afa/ and the easy deviant DEV 3 /Asa/, while DEV 1 and DEV 2 are equidistant morphings between standard stimulus and DEV 3.

Figure 4:
Figure 4 depicts an overview of the study design. The three participant groups are colored with pink (Group1: NLFC turned on), blue (Group 2: NLFC turned off), and gold (Group 3: normal-hearing older, NHO). Within three meetings, the hearing aids were individually fitted for the two hearing-impaired groups (Group 1 and Group 2) according to their audiograms as assessed in the first meeting. After three weeks, the measurement time point 1 (M1) was administered, where the IQ, the audiogram for Group 3 was assessed. Furthermore, the active oddball paradigm with the three different stimulus blocks was scheduled, while EEG was recorded. The normal-hearing group (Group 3) was tested without hearing aids, while the two moderately hearing-impaired groups (Group 1 and Group 2) were tested with their hearing aids, but in both groups NLFC was turned off for the testing, which allowed for the use of this session as a baseline measurement. After the session, NLFC was turned on only in Group 1. From this day, the hearing-impaired groups (in Group 1 with NLFC on and in Group 2 with NLFC off) were instructed to wear their hearing aids for at least eight hours each day, until the end of the study after three months and also during each testing at the following measurement time points. Measurement time points 2 (M2), 3 (M3), and 4 (M4) were administered at two week intervals, while measurement time point 5 (M5) was scheduled six weeks after measurement time point 4 (M4). During M2, M3, M4, and M5 participants took part only in the EEG testing with the active oddball task.

Figure 5:
The upper row shows the mean global field power (GFP) of each microstate (N2b-like, frontal P3b-like, and parietal P3b-like), separately for each measurement time point (M1, M2, M3, M4, and M5) and each group (NLFC on, NLFC off, and NHO), while the lower row shows the peak latency of the GFP. On the bottom the three microstates (N2b-like microstate, frontal P3b-like microstate, parietal P3b-like microstate) are depicted.

Figure 6:
Figure 6 shows the ERP data derived from electrode Cz for the easy deviant DEV 3 /Asa/ of stimulus Block 1, separately for each group (NLFC on in pink, NLFC off in blue, NHO in gold) and each measurement time point (M1, M2, M3, M4, and M5) for visual inspection.

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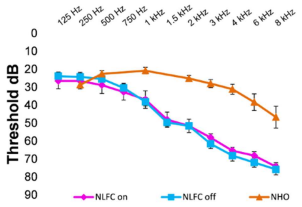

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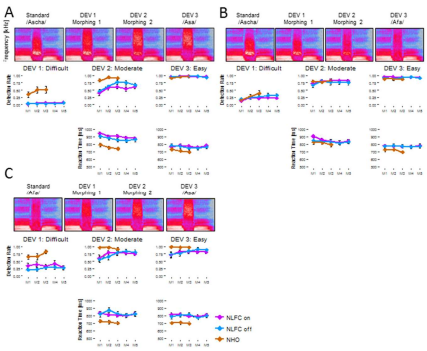

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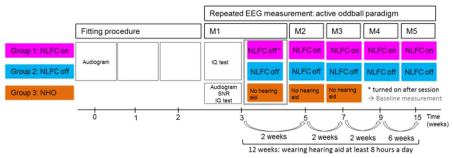

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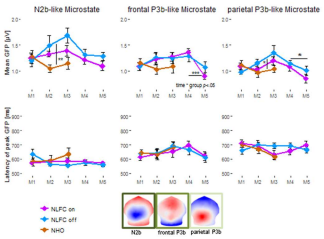

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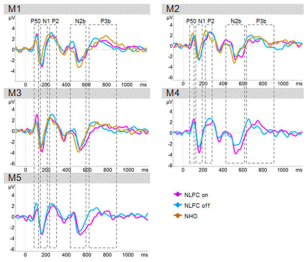

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Highlights

- Presbycusis leads to higher processing effort as evidenced by higher global-field power (GFP) in auditory evoked potentials (N2b, P3b).
- Hearing-impaired older adults have delayed longitudinal auditory plasticity as compared to normal-hearing older adults.
- It takes several weeks to acclimatize to a new hearing aid algorithm.

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